Study on the CO$_2$-EGS Coupling Model Affected by Porosity of Hot Dry Rock

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Abstract

To more realistically and accurately simulate the convective heat-transfer characteristics and heat-extraction performance of supercritical CO2 in an enhanced geothermal system (EGS), this study considers the variation characteristics of porosity and permeability in a hot dry rock reservoir under the coupled action of thermal, hydraulic, and mechanical fields. A THM-coupled CO2-EGS model incorporating the dynamic evolution of porosity in a hot dry rock reservoir is proposed and implemented through numerical simulation. The numerical results are compared with analytical solutions to verify the validity of the model. The seepage field, temperature field, stress field, and thermophysical parameters of supercritical CO2 are investigated and analyzed, and the interaction mechanism between supercritical CO2 and the hot dry rock reservoir is clarified. The results show that the porosity and permeability of hot dry rock change significantly with increasing system operation time, and supercritical CO2 can achieve favorable convective heat-transfer effects and heat-extraction performance in EGS. As supercritical CO2 rapidly diffuses through fractures and the reservoir matrix, the matrix temperature continuously decreases, producing a "high-temperature wave peak phenomenon" ; changes in matrix pore pressure and thermal contraction cause displacement of the EGS reservoir matrix, while permeability and porosity continuously increase and the flow velocity of supercritical CO2 in the matrix and main fractures continuously rises. Reservoir stress is continuously redistributed and reaches equilibrium after approximately 120 d of system operation. With changes in reservoir pressure and temperature, the thermophysical parameters of supercritical CO2 vary substantially and exhibit a nonlinear increasing trend.

Full Text

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Abstract: To more realistically and accurately simulate the convective heat-transfer characteristics and heat-extraction performance of supercritical CO_2 in an enhanced geothermal system (EGS), this study considers the variation characteristics of porosity and permeability in a hot dry rock reservoir under the coupled action of thermal, flow, and solid fields, and proposes a THM-coupled CO_2-EGS model that accounts for the dynamic evolution of porosity in hot dry rock reservoirs, implementing it by numerical simulation methods. The numerical calculation results are compared with analytical solutions to verify the validity of the model. The seepage field, temperature field, stress field of the model, and the thermophysical parameters of supercritical CO_2 are studied and analyzed, clarifying the interaction mechanism between supercritical CO_2 and the hot dry rock reservoir. The results show that the porosity and permeability of hot dry rock change significantly with increasing system operating time, and that supercritical CO_2 can achieve favorable convective heat-transfer effects and heat-extraction performance in EGS. As supercritical CO_2 rapidly diffuses through fractures and the reservoir matrix, the matrix temperature continuously decreases and a "high-temperature wave peak phenomenon" appears; changes in matrix pore pressure and thermal contraction cause displacement of the EGS reservoir matrix, permeability and porosity continuously increase, and the flow velocity of supercritical CO_2 in the matrix and main fractures continuously increases; the reservoir stress is continuously redistributed and reaches equilibrium at about 120 d of system operation; with changes in reservoir pressure and temperature, the thermophysical parameters of supercritical CO_2 vary considerably, showing a nonlinear increasing trend.

Keywords: hot dry rock; porosity; multi-field coupling; EGS; supercritical CO_2; convective heat transfer

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Study on the CO_2-EGS coupling model affected by porosity of hot dry rock

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Abstract: In order to achieve a more realistic and accurate simulation of the convective heat transfer characteristics and thermal extraction performance of supercritical CO_2 ($SCCO_2$) in the enhanced geothermal system (EGS), this study investigates the dynamic evolution of porosity and permeability in hot dry rock reservoirs under the combined influence of heat, flow, and solid fields. A THM-coupled CO_2-EGS model that accounts for the dynamic evolution of porosity in hot dry rock reservoirs is proposed, and numerical simulation methods are employed to implement it. The effectiveness of this model is validated by comparing numerical results with analytical solutions. This study delves into and analyzes the internal connection be-

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tween the multi-physics field and the thermal properties parameters of $SCCO_2$ to elucidate the interaction mechanism between $SCCO_2$ and hot dry rock reservoirs. The results show that $SCCO_2$ can achieve good convective heat transfer effect and thermal extraction performance in EGS. As $SCCO_2$ rapidly diffuses in fractures and matrix of the reservoir, the matrix temperature decreases continuously, thus leading to high-temperature peak phenomenon. Changes in matrix pore pressure and thermal shrinkage result in displacement of EGS reservoir matrix, increasing permeability and porosity continuously while the flow velocity of $SCCO_2$ increases in both matrix and main fractures. Reservoir stress redistributes continuously until reaching an equilibrium after approximately 120 days of system operation. With changes in reservoir pressure and temperature, significant variations occur in thermal properties parameters of $SCCO_2$, which show a nonlinear growth trend.

Key words: hot dry rock; porosity; multi-field coupling; EGS; $SCCO_2$; convective heat transfer

Enhanced geothermal systems are an effective means of exploiting hot dry rock. To date, there have been as many as 41 enhanced geothermal system (EGS) projects worldwide[^1]. However, owing to poor reservoir quality, low outlet temperature, induced earthquakes, and other reasons, many projects have ultimately had to be shut down[^2]. To solve the above problems, Brown[^3] was the first to propose using supercritical CO_2 (critical temperature about 31°C; critical pressure about 7.38 MPa) instead of water as the heat-exchange working medium for EGS, known as CO_2-EGS. Along this line of thought, Pruess[^4] used numerical simulation to study CO_2-EGS and preliminarily verified the feasibility of using supercritical CO_2 as the heat-exchange medium for EGS. In theory, the heat-exchange performance of supercritical CO_2 is superior to that of water[^5]. If CO_2-EGS can be commercialized, it will surely promote the development of clean energy worldwide and is of great significance to the global goal of carbon peak and carbon neutrality. However, EGS involves interactions among physical fields such as the seepage field, temperature field, stress field, and chemical field[^6][^7]. For example, changes in the seepage field lead to changes in fracture flow velocity and pressure in EGS, thereby causing changes in reservoir temperature and stress; changes in temperature and stress, in turn, cause changes in the fluid state and thermophysical parameters. In addition, the thermophysical parameters of supercritical CO_2 (density, specific heat capacity, thermal conductivity, dynamic viscosity) vary with temperature and pressure. When injected into EGS, it will induce more complex coupling effects and cause more complicated changes in multiple physical fields. Owing to the existence of the above issues, many characteristics of CO_2-EGS remain unclear at present, and a systematic theory and evaluation criteria have not yet been formed[^8]. In addition, because of the large start-up capital requirements, great construction difficulty, high maintenance cost, and difficulty in predicting production, no CO_2-EGS engineering project has yet been carried out in any country in the world. Therefore, at present, scholars at home and abroad mainly study CO_2-EGS through numerical simulation. Lei Hongwu et al.[^9] established a two-phase stable-flow model for a CO_2-H_2O system in a wellbore and proposed that the velocity difference between the gas phase and liquid phase has a decisive influence on the distributions of temperature and pressure in the wellbore. Sun Zhixue et al.[^10] established a THM multi-physics coupled mathematical model for CO_2 in a fracture system, and proposed that the characteristic parameters of thermal-storage fractures, spatial topological structure, and injection-production pressure are key factors affecting the operating life and heat-extraction efficiency of CO_2-EGS. Xue Bianwan[^11] established, based on the composite element method, a TH coupling algorithm for solving the seepage and heat-transfer characteristics inside fractured rock masses, and compared it with an approximate analytical solution, verifying the reliability of the model. Feng et al.[^12] proposed a new reservoir fracturing technology, constructed a CO_2-EGS thermal reservoir, and, according to the geological conditions of the Yangbajing geothermal field, established a numerical model to study the effects of parameters such as different injection pressures, temperatures, permeabilities, and well spacings on the convective heat-transfer characteristics of CO_2. Considering that most local geothermal resources are located in aquifers, Xiao et al.[^13], based on the momentum equation of compressible fluids and combined with the nonlinear parameters of CO_2, established an instantaneous model of CO_2 flow in a wellbore, and simulated the relationship between wellbore pressure and the nonlinear properties of CO_2 during the CO_2 injection process. Liao et al.[^14], based on the local thermal nonequilibrium method and DFN theory, constructed a THM coupled numerical model and studied the relationships among temperature variation, fluid flow, and fracture deformation in CO_2-EGS.

In addition to the above work, other studies have mainly focused on theoretical model analysis and derivation[^15^-^16], establishment of numerical models[^17], seepage and heat-transfer characteristics of fluids in EGS[^18], and parameter sensitivity analysis[^19]. However, at present, the research focus of most scholars is mainly on parameters that affect the heat-exchange performance of the model; therefore, most studies have adopted simplified methods to varying degrees for THM coupled models. For example, one-dimensional fitting formulas that consider only temperature effects are used to calculate the thermophysical parameters of supercritical CO_2, without considering fracture deformation and displacement. Although these simplified methods can reduce the difficulty of establishing and solving numerical models, they differ greatly from the actual situation and cannot truly reflect the convective heat-transfer performance in CO_2-EGS. Reservoir porosity changes with changes in the seepage field, temperature field, and stress field, and the variation characteristics of reservoir porosity are an important influencing factor leading to changes in seepage heat-transfer channels; they have a relatively large influence on the heat-exchange performance of CO_2-EGS and cannot be ignored. In summary, in order to make the analysis more realistic and accurate

simulate the convective heat-transfer characteristics of supercritical CO_2 in a hot dry rock reservoir and its heat-extraction performance. A THM-coupled CO_2-EGS model considering the dynamic evolution of porosity will be established based on a series of reasonable assumptions, and the numerical results will be compared with analytical solutions so as to validate the model.

In this study, the finite-element numerical simulation method is adopted to derive a THM-coupled CO_2-EGS model considering porosity variation characteristics. COMSOL Multiphysics is used for secondary development to solve the model, and its accuracy is verified. Finally, the convective heat-transfer characteristics and heat-extraction performance of the EGS model under the combined effects of porosity variation and supercritical CO_2 are obtained, with the aim of providing reference data for future practical EGS projects.

1 Establishment of the supercritical CO_2 injection-production heat-transfer coupled model

1.1 Basic assumptions and coupling relationships for model establishment

Based on the above description, it is necessary to neglect some variables that have relatively small effects on the system heat-transfer performance, and to introduce a series of reasonable assumptions, so as to reduce the computational difficulty as much as possible while more accurately simulating the convective heat-transfer characteristics of supercritical CO_2 in a hot dry rock reservoir and ensuring that the coupling effects among multiple physical fields are reflected. Meanwhile, the basis for model establishment is systematically described. Based on the discrete fracture network model, the reservoir is regarded as a fractured rock medium composed of a rock matrix and discrete fractures; fractures are treated using thin-layer elements to reduce the number of computational elements. Seepage between the matrix and fractures satisfies the second type of boundary condition and is represented by a mass source; temperature satisfies the third type of boundary condition and is represented by a heat source. The fracture distribution in a hot dry rock reservoir is uncertain, and at present its true distribution still cannot be obtained. Studies have shown[20] that most of the coordinates of the center points of natural fractures in hot dry rock reservoirs follow a uniform distribution, and their trace lengths and orientations

Fig. 1 Coupling relationship of THM

Figure 1: Fig. 1 Coupling relationship of THM

follow normal distributions; hydraulic fractures may be assumed to be the same as natural fractures. Because granite has relatively large elastic and bulk moduli and small deformation, linear-elastic material assumptions may be adopted to describe the mechanical properties of the solid. It is assumed that the hot dry rock reservoir can always maintain a high-pressure state. When liquid CO_2 is injected into the hot dry rock reservoir under high pressure, its temperature gradually increases; however, because the reservoir pressure is always higher than the critical pressure, CO_2 cannot vaporize, and gradually transforms from the liquid state to the supercritical state. According to its p–v diagram, the CO_2 curve at this time does not pass through the gas–liquid two-phase region; the latent heat of phase change is zero, and the entire process is in the supercritical state. Therefore, the heat-source term caused by latent heat of phase change in its energy equation is zero and may be neglected. In addition, because the mass of CO_2 is relatively small, its gravity and inertial force are not considered. According to the assumptions, the reservoir matrix can be regarded as a porous medium; the aperture of discrete fractures is only on the millimeter scale, so the seepage of supercritical CO_2 fluid in the reservoir matrix and fractures can both be regarded as saturated single-phase laminar flow. Darcy' s law is used to describe its flow, and fracture seepage satisfies the cubic law. Since the scale of an EGS is relatively large, supercritical CO_2 and the hot dry rock reservoir have sufficient time to exchange heat and can completely reach thermal equilibrium before flowing out of the production well. Therefore, it is not necessary to adopt different energy equations for supercritical CO_2 and the hot dry rock reservoir separately; only a local thermal equilibrium model is needed to describe heat transfer in the EGS system. In addition, system heat transfer considers the effects of heat conduction and heat convection. According to the above assumptions, a THM-coupled partial differential control-equation system is established. The model coupling relationship is shown in Fig. 1.

Fig. 1 Coupling relationship of THM

1.2 THM coupled governing equations

The seepage of supercritical CO_2 in a hot dry rock reservoir follows Darcy' s law. According to the law of conservation of mass, the matrix seepage governing equation[21] is

$$\frac{\partial \rho_{\mathrm{L}} \varphi}{\partial t} + \nabla \cdot \left[\rho_{\mathrm{L}} \cdot \left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right)\right] = Q_{\mathrm{m}} \qquad (1)$$

where ρ_{L} is the density of CO_2; φ is the porosity of the rock matrix; $\rho_{\mathrm{L}}\varphi$ denotes the mass of CO_2 in a unit volume of rock matrix; k is the permeability of the rock matrix; μ is the dynamic viscosity of CO_2; p is pressure; L is the relative height; and Q_m is the source term.

For the reservoir temperature field, the fluid governing equation for CO_2 is

$$\frac{\partial(\rho_L c_L \varphi \Delta T_L)}{\partial t} = -\nabla \cdot \left[\rho_L c_L \left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right) T_L\right] + \nabla \cdot [\lambda_L \varphi \nabla T_L] + Q_L \tag{2}$$

where c_L is the constant-pressure specific heat capacity of CO_2; ΔT_L is the change in CO_2 temperature; λ_L is the thermal conductivity of CO_2; and Q_L is the source term.

Considering that the reservoir porosity is small, in order to simplify the calculation, the influence of the volume of the pore portion on heat transfer in the rock matrix is neglected. Then the temperature-field governing equation of the rock matrix[22] is

$$\rho_s c_s \frac{\partial(\Delta T_s)}{\partial t} = T_s \alpha_T K \frac{\partial \varepsilon_v}{\partial t} + \lambda_s [\nabla \cdot (\nabla T_s)] + Q_s \tag{3}$$

where: ρ_s is the density of the rock matrix; c_s is the constant-pressure specific heat capacity of the rock matrix; λ_s is the thermal conductivity of the rock matrix; T_s is the temperature of the rock matrix; α_T is the thermal expansion coefficient of the rock matrix; K is the bulk modulus of the rock mass; ε_v is the volumetric strain of the rock matrix; and Q_s is the source term.

According to the local thermal-equilibrium theory [23], the governing equation for the total temperature field of the system is

$$\begin{aligned}\frac{\partial(\rho_L c_L \varphi \Delta T)}{\partial t} + \rho_s c_s \frac{\partial(\Delta T)}{\partial t} &= -\nabla \cdot \left[\rho_L c_L \left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right) T\right] + \nabla \cdot [\lambda_L \varphi \nabla T] \\ &\quad + \lambda_s \nabla \cdot (\nabla T) + T \alpha_T K \frac{\partial \varepsilon_v}{\partial t} + Q_T\end{aligned} \tag{4}$$

where $Q_T = Q_s + Q_L$.

Because changes in the temperature field of the rock matrix generate thermal stress, and changes in the seepage field lead to variations in the CO_2 flow velocity and pore pressure, considering the above factors comprehensively, the governing equation for the rock deformation stress field under the influence of thermal expansion and pore pressure [24] is

$$G u_{i,j} + (\lambda + G) u_{j,ji} - \alpha_B p_i - \alpha_T T_{s,i} + F_i = 0 \tag{5}$$

where: G is the shear modulus; λ is the first Lamé constant; $u_{i,j}$ and $u_{j,ji}$ are displacement components; α_B is the Biot-Willis coefficient; p_i is the pressure component; and $T_{s,i}$ is the temperature component. Among them, $G = E/2(1+\nu)$, $\lambda = E\nu/[(1+\nu)(1-2\nu)]$, $\alpha_B = 1-K/K_s$, $K = E/[3\times(1-2\mu)]$, where K is the bulk modulus of the rock mass, K_s is the bulk modulus of the rock matrix, E is the elastic modulus, and ν is Poisson' s ratio.

The governing equation for CO_2 seepage in fractures of a dry hot-rock reservoir [21,25] is

$$d_f \frac{\partial}{\partial t}(\rho_L \varphi_f) + \nabla_1 \cdot \left(d_f \rho \frac{k_f}{\mu} \nabla_1 p \right) = d_f Q_f \qquad (6)$$

where: d_f is the fracture aperture; φ_f is the fracture porosity; ∇_1 is the tangential gradient of the fracture; k_f is the fracture permeability; p is pressure; and Q_f is the CO_2 mass source term flowing into the fracture. Fracture seepage satisfies the cubic law.

The governing equation for the fracture temperature field of a dry hot-rock reservoir [26] is

$$d_f \frac{\partial}{\partial t}(\rho_s c_s T) - \nabla_1 \cdot (d_f \lambda_f \nabla_1 T) - d_f \rho_L c_L \left(\frac{k_f}{\mu} \nabla_1 p \right) \nabla_1 T = d_f Q_h \qquad (7)$$

where: λ_f is the thermal conductivity of the fracture; Q_h is the heat source term transferred into the fracture; it satisfies Newton' s cooling formula, and the heat-transfer coefficient is taken from the literature [27].

The reservoir porosity φ and permeability k are affected by the seepage field, temperature field, and stress field, and their dynamic evolution model [28] can be expressed as

$$\varphi = 1 - (1-\varphi_0)\exp\left[-\frac{(p-p_0)}{K_s} + \alpha_T (T-T_0) - (\varepsilon_v - \varepsilon_{v0}) \right] \qquad (8)$$

$$k = k_0 \left(\frac{1}{\varphi_0} - \left(\frac{1-\varphi_0}{\varphi_0} \right) \cdot \exp\left[-\frac{(p-p_0)}{K_s} + \alpha_T (T-T_0) - (\varepsilon_v - \varepsilon_{v0}) \right] \right)^3 \qquad (9)$$

where: φ_0 is the initial porosity of the rock matrix; p_0 is the initial pressure; T_0 is the initial formation temperature; and ε_{v0} is the initial strain.

First, the matrix seepage-field governing equation considering the effects of porosity and permeability is constructed. Substituting Eqs. (8) and (9) into Eq. (1) and rearranging gives

$$-\rho_L(1-\varphi_0)\exp\left[-\frac{p-p_0}{K_s}+\alpha_T(T-T_0)-(\varepsilon_v-\varepsilon_{v0})\right]\cdot\left(-\frac{1}{K_s}\frac{\partial P}{\partial t}+\alpha_T\frac{\partial T}{\partial t}-\frac{\partial \varepsilon_v}{\partial t}\right)-\nabla\cdot\left(\frac{k}{u}\rho_L\nabla p\right)=Q_m \quad (1$$

In COMSOL Multiphysics, the coefficient-form partial differential equation provided by the interface is

$$e_a\frac{\partial^2 p}{\partial t^2}+d_a\frac{\partial p}{\partial t}+\nabla\cdot(-c\nabla p-\alpha p+\gamma)+\beta\cdot\nabla p+ap=f \qquad (11)$$

where: e_a is the mass coefficient; d_a is the damping coefficient; c is the diffusion coefficient; α is the conservative flux; γ is the conservative flux source; β is the convection coefficient; a is the absorption coefficient; and f is the source term.

Let

$$M=\exp\left[-\frac{p-p_0}{K_s}+\alpha_T(T-T_0)-(\varepsilon_v-\varepsilon_{v0})\right] \qquad (12)$$

To maintain the same form as Eq. (11), transposing Eq. (10) gives

$$\rho_L(1-\varphi_0)M\frac{1}{K_s}\frac{\partial p}{\partial t}+\nabla\cdot\left(-\frac{k}{u}\rho_L\nabla p\right)=\rho_L(1-\varphi_0)M\left(\alpha_T\frac{\partial T}{\partial t}-\frac{\partial \varepsilon_v}{\partial t}\right)+Q_m \qquad (13)$$

where: $e_a=0$; $d_a=\rho_L(1-\varphi_0)M\frac{1}{K_s}$; $c=\frac{k}{u}\rho_L$; $\alpha=0$; $\gamma=0$; $\beta=0$; $a=0$; $f=\rho_L(1-\varphi_0)M\left(\alpha_T\frac{\partial T}{\partial t}-\frac{\partial \varepsilon_v}{\partial t}\right)+Q_m$.

Similarly, for the temperature field, ρ_L, λ_L, and c_L may be treated as constants, and Eq. (4) can be simplified to Eq. (14), namely

$$\begin{aligned}\rho_s c_s\frac{\partial T}{\partial t}+\rho_L c_L\varphi\frac{\partial T}{\partial t}+\rho_L c_L\Delta T\frac{\partial \varphi}{\partial t}=-\nabla\cdot\left[\rho_L c_L\left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right)T\right]+\\ \nabla\cdot[(\lambda_s+\lambda_L\varphi)\nabla T]+T\alpha_{TK}\frac{\partial \varepsilon_v}{\partial t}+Q_T\end{aligned} \qquad (14)$$

Substituting Eq. (9) into Eq. (14) and rearranging gives

$$
\begin{aligned}
&(\rho_{\mathrm{s}}c_{\mathrm{s}}+\rho_{\mathrm{L}}c_{\mathrm{L}}\varphi)\frac{\partial T}{\partial t}-\rho_{\mathrm{L}}c_{\mathrm{L}}\Delta T(1-\varphi_0)\cdot\\
&\quad\left(-\frac{1}{K_{\mathrm{s}}}\frac{\partial p}{\partial t}+\alpha_{\mathrm{T}}\frac{\partial T}{\partial t}-\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t}\right)M\\
&=-\nabla\cdot\left[\rho_{\mathrm{L}}c_{\mathrm{L}}\left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right)T\right]+\nabla\cdot[(\lambda_{\mathrm{s}}+\lambda_{\mathrm{L}}\varphi)\nabla T]+\\
&\quad T\alpha_{\mathrm{T}}K\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t}+Q_{\mathrm{T}}
\end{aligned}
\tag{15}
$$

Splitting and combining like terms yields

$$
\begin{aligned}
&\left[(\rho_{\mathrm{s}}c_{\mathrm{s}}+\rho_{\mathrm{L}}c_{\mathrm{L}}\varphi)-\alpha_{\mathrm{T}}\rho_{\mathrm{L}}c_{\mathrm{L}}\Delta T(1-\varphi_0)M\right]\frac{\partial T}{\partial t}\\
&=\nabla\cdot\left\{(\lambda_{\mathrm{s}}+\lambda_{\mathrm{L}}\varphi)\nabla T-\left[\rho_{\mathrm{L}}c_{\mathrm{L}}\left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right)T\right]\right\}+\\
&\quad\alpha_{\mathrm{T}}K\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t}T-\rho_{\mathrm{L}}c_{\mathrm{L}}\Delta T(1-\varphi_0)\left(\frac{1}{K_{\mathrm{s}}}\frac{\partial p}{\partial t}+\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t}\right)M+Q_{\mathrm{T}}
\end{aligned}
\tag{16}
$$

In COMSOL Multiphysics, the equation provided by the coefficient-form partial differential equation interface is

$$
e_{\mathrm{a}}\frac{\partial^2 T}{\partial t^2}+d_{\mathrm{a}}\frac{\partial T}{\partial t}+\nabla\cdot(-c\nabla T-\alpha T+\gamma)+\beta\cdot\nabla T+aT=f \tag{17}
$$

where:

$$
e_{\mathrm{a}}=0;\gamma=0;\beta=0;
$$

$$
d_{\mathrm{a}}=\left[(\rho_{\mathrm{s}}c_{\mathrm{s}}+\rho_{\mathrm{L}}c_{\mathrm{L}}\varphi)-\alpha_{\mathrm{T}}\rho_{\mathrm{L}}c_{\mathrm{L}}\Delta T(1-\varphi_0)M\right];
$$

$$
c=-(\lambda_{\mathrm{s}}+\lambda_{\mathrm{L}}\varphi);\alpha=\rho_{\mathrm{L}}c_{\mathrm{L}}\left(-\frac{k}{\mu}\frac{\partial p}{\partial L}\right);a=\alpha_{\mathrm{T}}K\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t};
$$

$$
f=-\rho_{\mathrm{L}}c_{\mathrm{L}}\Delta T(1-\varphi_0)\left(\frac{1}{K_{\mathrm{s}}}\frac{\partial p}{\partial t}+\frac{\partial\varepsilon_{\mathrm{V}}}{\partial t}\right)M+Q_{\mathrm{T}}.
$$

1.3 Thermophysical parameters of supercritical CO_2

The thermophysical parameters of supercritical CO_2 include dynamic viscosity μ, density ρ, specific heat capacity c_L, and thermal conductivity λ_L, all of which are binary functions of temperature and pressure and have important effects on the convective heat-transfer performance of the system. By using various equations of state (such as the S-W equation) and measured data, fitting expressions for the thermophysical parameters of supercritical CO_2 can be obtained and thereby used to characterize them. The binary analytical functions are imported into COMSOL Multiphysics and calculated using Eqs. (18)-(21)[29].

$$\mu(T,p) = 7.14\times10^{-9}T^2 - 5.642\times10^{-6}T - 5.71\times10^{-9}p^2 + 2.186\times10^{-6}p + 0.0011 \tag{18}$$

$$\rho_L(T,p) = 0.00036T^3 - 0.3693T^2 + 122T - 0.333p^2 + 32.54p - 12720 \tag{19}$$

$$c_L(T,p) = -4.9\times10^{-5}T^3 + 0.084T^2 - 49.11T + 0.47p^3 - 42.1p^2 + 1200p + 276.3 \tag{20}$$

$$\lambda_L(T,p) = -1.75\times10^{-8}T^3 + 2.29\times10^{-5}T^2 - 0.01T - 1.89\times10^{-5}p^3 + 0.0007p^2 - 0.006p + 1.46 \tag{21}$$

1.4 THM geometric model and solution conditions

Based on the above theory, this study establishes a two-dimensional discrete-fracture double-well EGS numerical model perpendicular to the direction of gravity, as shown in Fig. 2(a). According to the assumptions, the fracture parameters can be treated as random variables, and a random fracture generation model is written using the Monte Carlo method. A rectangular region of 100 m × 100 m is established (with the coordinate origin located at the lower-left corner of the region), and two sets of random fractures are generated in the middle of the region, with dip angles of 0° and 90°, mean trace length of 10, and variance of 15. To ensure convergence of the numerical calculation, overlapping fractures and fractures with excessively small spacing are deleted, and the final random fracture distribution is shown in Fig. 2(b). It is assumed that the dry-hot-rock reservoir is buried at a depth of 3 000 m, with an initial temperature of 200 °C. The blue dot in the upper-left corner denotes the injection well, with well-center coordinates $(10\ \text{m}, 80\ \text{m})$; the red dot in the lower-right corner denotes the production well, with well-center coordinates $(90\ \text{m}, 20\ \text{m})$; and the well radius is 2 m. For the temperature boundary, the outer boundary is set as a thermally insulated boundary, with heat flux equal to 0; the initial reservoir

Fig. 2(a) Three-dimensional schematic diagram: injection well, production well, ground surface, fractured rock mass, 3 000 m, 100 m

Figure 2: Fig. 2(a) Three-dimensional schematic diagram: injection well, production well, ground surface, fractured rock mass, 3 000 m, 100 m

Geometric model: (b) two-dimensional model diagram

Figure 3: Geometric model: (b) two-dimensional model diagram

temperature is set to 200 °C; and the injection temperature is set to 35 °C. For the seepage boundary, the outer boundary is set as a no-flow boundary; the CO_2 injection mode is a pressure inlet; the initial reservoir pressure is 10 MPa; the injection-well pressure is set to 20 MPa, and the production-well pressure is set to 8 MPa; the initial matrix porosity φ_0 is set to 0.02, and the initial matrix permeability is set to 10^{-18} m^2. For the stress boundary: according to the reservoir burial depth, the average overburden density is set between 15 ∼ 20 kN/m^3; an initial geostress of 60 MPa can be applied to the upper and lower boundaries, and an initial geostress of 55 MPa to the left and right boundaries; the lower boundary is a fixed support, and both the normal and tangential displacements are constrained. Parameters such as elastic modulus, Poisson' s ratio, and bulk modulus are regarded as constants. The model parameter values are shown in Table 1.

(a) Three-dimensional schematic diagram

(b) Two-dimensional model diagram

Fig. 2 Geometric model

Tab. 1 Parameters of numerical simulation

Simulation parameter	Unit	Value
Rock-matrix density ρ_s	kg/m^3	2 700
Rock-matrix specific heat capacity c_s	J/(kg · °C)	1 000
Rock-matrix thermal conductivity λ_s	W/(m · °C)	2.5
CO_2 density ρ_L	kg/m^3	$\rho_L(T, p)$
CO_2 constant-pressure specific heat c_L	J/(kg · °C)	$c_p(T, p)$

Simulation parameter	Unit	Value
CO_2 thermal conductivity λ_L	$W/(m\cdot°C)$	$\lambda_L(T,p)$
CO_2 dynamic viscosity μ	$Pa\cdot s$	$\mu(T,p)$
Rock elastic modulus E	GPa	50
Rock Poisson' s ratio ν	1	0.25
Thermal expansion coefficient α_T	1/°C	3×10^{-6}
Rock-matrix bulk modulus	GPa	55
Rock bulk modulus	GPa	$E/[3\times(1-2\cdot\mu)]$
Biot coefficient	1	$1-K/K_s$
Production-well pressure p_{out}	MPa	8
Fracture aperture ρ_L	mm	0.01
Fracture porosity φ_f	1	1
Fracture permeability k_f	m^2	$\varphi_f^2/12\times f_f$
Roughness coefficient f_f	1	1

By calling the coefficient-form PDE interface built into COMSOL Multiphysics, the governing equations for the seepage field and temperature field are constructed; the Solid Mechanics Interface is used to construct the governing equations for the stress field. The model adopts two study steps, namely steady-state solution and transient solution. For the transient solver, the transient degrees of freedom are calculated by the time-integration method, the maximum number of iterations is set to 100, the solution time is 3 650 d, the default time step is 1 d, the relative tolerance is 1, and the implicit backward differentiation formula (BDF) scheme is used for time discretization, with the initial step size set to 0.000 001 d and the maximum BDF order set to 4; all other parameters use default values. The nonlinear method of the fully coupled solver uses the automatic highly nonlinear Newton method, the minimum damping factor is set to 10^{-10}, and the direct solver uses the PARDISO solver. After the steady-state solver obtains the results, the results are used as the initial values for the transient solver to compute the model. Calculations are performed with 20 634, 25 781, 30 426, and 35 214 meshes, respectively. Verification shows that when the mesh reaches 25 781 elements, the accuracy of the calculation results can be guaranteed.

1.5 THM model verification

For an EGS, after the thermal reservoir has been constructed, the geostress reaches equilibrium and the stress field is basically in a stable state. After heat exchange begins, fluid seepage and heat exchange cause some changes in the stress field. For example, pore-pressure changes caused by fluid pressure affect stress, and matrix thermal shrinkage caused by fluid heat exchange affects displacement. Overall, however, the above effects are quite limited, and the changes in the stress field are not large. Correspondingly, because the elastic modulus of granite is sufficiently large, seepage and heat transfer are not enough to cause large changes in the stress field, and thus will not conversely affect seepage and heat transfer. In summary, the influence of the stress field exists, but it does not play a decisive role in convection and heat exchange in EGS. Therefore, a method for solving fracture seepage heat transfer proposed by Barends[^30] can be used to verify the model. The basic assumptions of this analytical method are as follows: the rock matrix is regarded as a homogeneous infinite medium located on a two-dimensional spatial plane in the x and y directions, and the initial temperature distribution is uniform; the fracture is regarded as a thin layer, and heat conduction of the fluid in the fracture along the normal direction is not considered; the thermophysical parameters of the injected fluid are always constants and do not vary with temperature and pressure. Based on the above assumptions, the analytical solution expression for the temperature T_{L} at a point x along the fracture is as follows.

$$T_{\mathrm{L}} = T_0 + (T_{\mathrm{in}} - T_0)\,\mathrm{erfc}\left(\frac{\lambda_{\mathrm{s}}/\rho_{\mathrm{L}} c_{\mathrm{L}}}{2\sqrt{\lambda_{\mathrm{s}}/\rho_{\mathrm{s}} c_{\mathrm{s}}}\,(u_{\mathrm{L}} t - x)}\right) \cdot U\left(t - \frac{x}{u_{\mathrm{L}}}\right) \qquad (22)$$

where: T_{L} is the temperature at fracture coordinate x (the inlet coordinate is 0); T_0 is the initial temperature of the rock matrix; T_{in} is the fluid injection temperature; ρ_{L} is the fluid density; ρ_{s} is the rock-matrix density; λ_{s} is the rock-matrix thermal conductivity; c_{L} is the fluid specific heat capacity; c_{s} is the rock-matrix specific heat capacity; u_{L} is the fluid velocity; t is time; $\mathrm{erfc}(\cdot)$ is the complementary error function; and $U(\cdot)$ is the unit step function.

Using MATLAB software to write a program, the above analytical expression can be solved. Because this analytical expression does not consider the influence of the stress field, the supercritical CO_2 injection–production heat-exchange THM coupling model established in this study is simplified, and a two-dimensional TH numerical model is established. Since, in this analytical solution, parameters such as fluid density and specific heat capacity are constants, whereas supercritical

The thermophysical parameters of CO_2 vary greatly; therefore, when verifying the model, water, whose thermophysical-property variations are relatively small,

Fig. 3 Schematic diagram of the verifying model

Figure 4: Fig. 3 Schematic diagram of the verifying model

Fig. 4 Comparison between numerical and analytical solutions

Figure 5: Fig. 4 Comparison between numerical and analytical solutions

is used as the heat-exchange medium. Although this cannot fully reflect the convective heat-transfer characteristics of supercritical CO_2, it can capture the trend of seepage heat transfer. Meanwhile, to ensure to the greatest extent that the initial and boundary conditions of the numerical model are consistent with the analytical expressions, the geometric model is set as a rectangular region of 200 m × 200 m, whose schematic is shown in Fig. 3. The upper and lower rectangles represent the rock matrix, and the middle rectangle represents a horizontal smooth fracture with an aperture of d_f. The fracture–matrix interface satisfies the convective heat-transfer boundary condition; the left end of the fracture is the fluid inlet and the right end is the fluid outlet. Except for the outlet and inlet, all other boundaries are set as adiabatic and no-flow boundaries. A total of 25 351 grid cells are divided, and the average grid quality reaches 0.821 4. The main computational parameters and initial conditions required for the analytical expression and numerical model are shown in Table 2. Four points, A, B, C, and D, on the fracture are selected as probe points (their distances from the fracture inlet are 40, 80, 120, and 160 m, respectively). The comparison between the numerical and analytical solutions at these points is shown in Fig. 4. It can be seen from the figure that the calculation results of this model are highly consistent with the analytical solution, thereby verifying the feasibility of the injection–production THM coupled model established in this study.

Fig. 3 Schematic diagram of the verifying model

Table 2 Parameters of the verifying model

Parameter	Unit	Value
Initial temperature T_0	℃	200
Injection temperature T_{in}	℃	35
Fluid density ρ_L	kg/m^3	1 000
Rock density ρ_s	kg/m^3	2 700
Rock thermal conductivity λ_s	W/(m · ℃)	3
Fluid specific heat capacity c_L	J/(kg · ℃)	4 200
Rock specific heat capacity c_s	J/(kg · ℃)	1 000
Flow velocity	m/s	0.005

(a) Temperature changes with time at different monitoring points

(b) Temperature changes along the x-axis at different injection times

Fig. 4 Comparison between numerical and analytical solutions

2 Results and Discussion

2.1 Analysis of System Heat-Exchange Performance

Without considering heat flux through the four surrounding boundaries, with the injection of supercritical CO_2, a medium-low-temperature region gradually forms in the reservoir and rapidly spreads along the fracture and the rock matrix; after a certain period of time, it spreads to the production well. The cloud maps of reservoir temperature distribution at different times are shown in Fig. 5. When the system has operated for 0.1 a, CO_2 diffuses rapidly along the fracture, and a low-temperature region begins to form in the reservoir. When the system has operated for 1 a, the farthest affected region has reached the vicinity of the production well. When the system has operated for 3 a, the maximum reservoir temperature begins to decrease to 199 ℃, and the area of the medium-low-temperature region further increases. When the system has operated for 5 a, the area of the medium-low-temperature region no longer increases significantly, but the area of the low-temperature region further expands, and the maximum reservoir temperature drops to 191 ℃. When the system has operated for 7–10 a, the area of the medium-low-temperature region shows no obvious change, and the blue low-temperature region has expanded to the production well, without thermal breakthrough.

For the convenience of subsequent analysis, a two-dimensional cross-section passing through the injection well and the production well is selected in the model (as shown by the green line segment in Fig. 2), and the temperature along the straight line connecting the two wells is analyzed. The results are shown in Fig. 6.

shown. In the early stage of system operation, CO_2 rapidly diffuses along the fractures after injection, and the formation temperature near the injection well drops rapidly. Strong fluctuations occur near the injection well ($x < 40$ m). When the system has operated for 1 a, the temperature near the injection well has decreased to about 75 ℃, and the affected range has expanded to 80 m away from the injection well; a "high-temperature wave peak" appears, as shown at positions and in Fig. 6. When operated for 3 a, the temperature near the injection well further decreases, and the overall temperature along the line drops sharply, with the maximum temperature between the wells not exceeding 160 ℃. The above phenomenon is relatively obvious in the early stage of system operation, reaches its peak in the third year, and then gradually weakens and tends to become gentle. This phenomenon is mainly caused by the fractures cutting the reservoir rock mass into several independent blocky regions. When CO_2 flows in the fractures, the heat in the reservoir rock mass of the independent blocky regions close to the fractures can be rapidly carried away, so the temperature decreases rapidly. However, because the thermal conductivity of the rock is small, heat cannot be transferred in time, causing the temperature reduction rate in the parts far from the fractures to be lower than the fracture rate, thereby leading to locally higher temperatures and forming a "high-temperature

Fig. 5 Temperature variation over time

Figure 6: Fig. 5 Temperature variation over time

Fig. 6 The temperature of the straight line connecting the two wells over time

Figure 7: Fig. 6 The temperature of the straight line connecting the two wells over time

wave peak” effect.

图 5　温度随时间变化

Fig. 5　The variation of temperature over time

图 6　两井所连直线温度随时间变化

Fig. 6　The temperature of the straight line connecting the two wells over time

Figure 7 gives the relevant parameters of the system’ s heat-production performance. It can be seen that the average reservoir temperature decreases nearly linearly with CO_2 injection and extraction, whereas the production-well temperature reaches a relatively large velocity gradient only after about 1 a of injection. When the system has operated for 10 a, the average production-well temperature decreases to 87 ℃, and the average reservoir temperature also decreases from 200 ℃ to 103 ℃.

图 7　系统采热性能

Fig. 7　The thermal performance of the system

The calculation formula for the reservoir heat-extraction rate W is

$$W = hQ,$$

$$h = mc_L(T_0 - T),$$

$$Q = Q_s + Q_f = \iint_A u_s \rho_L \, dA + d_f \int_L u_L \rho_L \, dl \qquad (23)$$

where h is the heat absorbed per unit mass of CO_2; Q is the total mass flow rate of CO_2; u_s is the CO_2 flow velocity in the matrix; and u_L is the CO_2 flow velocity

Fig. 7 The thermal performance of the system

Figure 8: Fig. 7 The thermal performance of the system

Fig. 8 Pressure distribution at different time points

Figure 9: Fig. 8 Pressure distribution at different time points

in the fracture. Because the specific heat capacity and density of supercritical CO_2 vary with temperature and pressure, the relationship between production-well temperature and heat-extraction rate is not nonlinear. The maximum heat-extraction rate can reach 2.6 MW; in the early stage, a relatively rapid heat-extraction rate is maintained, and it rapidly decreases to 1.81 MW only when the system has operated for about 1 000 d. In the later stage, its extraction rate decreases, and when the system has operated for 10 a, it is about 1.4 MW.

2.2 Analysis of the characteristics of system pressure variation

The reservoir pressure continuously changes with CO_2 injection, and changes in reservoir pressure also cause parameters such as CO_2 flow velocity, density, and volume to change; the interaction between the two ultimately leads to changes in the system heat-exchange performance. Figure 8 shows cloud maps of pressure changes in the reservoir at different times. Because there is a pressure difference as high as 12 MPa between the two wells, and the permeability of the granite is low, the seepage velocity in the matrix is relatively slow. Supercritical CO_2 mainly diffuses along the fractures, and the fractures are filled only on the first day of system operation. The pressure changes with reservoir coordinates: the pressure is relatively high near the injection well, then continuously dissipates, and reaches its minimum at the production well. As injection time increases, the volume of CO_2 in the reservoir continuously increases, and the high-pressure region near the injection well extends along the

the fractures continuously expand. When the injection duration is 5 d, the supercritical CO_2 entering through the fractures penetrates through the matrix and forms a transition zone at the middle position between the two wells. When the injection time is 10 d, the areas of both the high-pressure zone and the transition zone further increase. When the injection time is 30 d, the transition zone no longer spreads toward the production well; however, because the upper and lower boundaries are set as no-flow boundaries, the pressure difference between the boundary pressure and the injection well is relatively small, and the pressure decreases more slowly in this direction. Therefore, the transition zone further expands in the y direction. When the injection time is 120 d, the high-pressure zone and the transition zone no longer expand, and the pressure in the reservoir reaches equilibrium.

图 8 不同时刻压力分布

Fig. 8 Pressure distribution at different time points

Fig. 9 The volume strain at different time points

Figure 10: Fig. 9 The volume strain at different time points

2.3 Analysis of the variation characteristics of the system stress field

The stress field of the EGS reservoir gradually changes with time. The causes of this change are mainly reflected in two aspects: on the one hand, the pore-pressure change after the injection of supercritical CO_2 and the thermal stress change caused by heat exchange; on the other hand, the geostress caused by long-term action (the external stresses on the upper-lower and left-right boundaries are 60 and 55 MPa, respectively). The variation in pore pressure has already been obtained from Fig. 8 and therefore will not be described here. Because the elastic modulus of the reservoir rock is relatively large (50 GPa), the volumetric strain caused by geostress is relatively small. The changes in the stress field in the EGS are mostly caused by thermal contraction of the rock matrix. Therefore, studying the variation of the rock volumetric strain with time can explain the problem, as shown in Fig. 9.

It can be seen that the variation of volumetric strain with time is highly consistent with the variation of temperature. It also gradually spreads along the throughgoing fracture, and the lower the temperature of a region, the greater the variation in volumetric strain. At the initial moment, the maximum volumetric strain of the reservoir is 1.91×10^{-4}. As heat exchange proceeds, it continuously decreases and changes from a positive value to a negative value, that is, from a thermal-expansion state to a thermal-contraction state. When the system has operated for 10 a, the minimum volumetric strain is approximately -4.52×10^{-3}; at this time, most regions of the entire reservoir are in a thermal-contraction state. In summary, it can be preliminarily confirmed that thermal contraction is the main factor causing changes in the reservoir stress field, but further analysis is still required.

图 9 不同时刻的体应变

Fig. 9 The volume strain at different time points

2.4 Analysis of system convective heat-transfer mechanism

Based on the contour maps of the reservoir temperature field, pressure field, and volumetric strain, a qualitative analysis can be carried out. In the model, the throughgoing fracture is selected for targeted analysis, as indicated by the red part in Fig. 2; it is hereafter referred to as the "main fracture." The convective heat-transfer performance of the system is affected in the following respects: first, the more throughgoing fractures contained in the main fracture, the smaller the resistance to the seepage of supercritical CO_2 in the fracture, and the larger the seepage surface area between it and the reservoir matrix, which leads to a continuously increasing diffusion rate of supercritical CO_2 in the reservoir; second, because supercritical CO_2 continuously removes heat from the reservoir, the thermal-expansion effect of the reservoir matrix is weakened, causing changes in reservoir porosity and permeability; third, changes in reservoir temperature and pressure lead to changes in the thermophysical parameters of supercritical CO_2, thereby causing changes in its density and volume and ultimately causing changes in pore pressure.

Figures 10 and 11 respectively show the temporal variations of the average flow velocity of supercritical CO_2 in the main fracture and in the reservoir matrix, and compare them with the flow velocities obtained without considering changes in porosity and permeability. For the main fracture, because of contraction of the rock matrix, the flow velocity of supercritical CO_2 gradually increases. Its variation pattern remains consistent with the matrix flow velocity. The average flow velocity is approximately 0.246 1 m/s, which is higher than the average flow velocity of 0.245 77 m/s when changes in porosity and permeability are not considered. Similarly, in the rock matrix, the average flow velocity of supercritical CO_2 increases approximately linearly with time, and the time-averaged value is approximately 5.94×10^{-9} m/s, higher than the average flow velocity of 5.46×10^{-9} m/s when changes in porosity and permeability are not considered. To explain the above phenomena, it is necessary to separately study the relationships between the three physical fields and the variation characteristics of porosity. According to the above study, for the seepage field, the reservoir pressure can reach within less than one year.

to an equilibrium state; after equilibrium is reached, the pressure term in the dynamic evolution model for porosity contributes 0. Therefore, the influence of reservoir pressure on changes in matrix flow velocity can be neglected. For the stress field, because granite has a relatively large elastic modulus and bulk modulus, its volumetric strain is relatively small, and its influence on the matrix flow velocity is limited. For the temperature field, because the reservoir temperature changes considerably, the resulting large change in thermal stress causes thermal contraction of the rock matrix, thereby expanding seepage channels. To verify this conjecture, the porosity and permeability of the reservoir were analyzed. Figure 12 gives the curves of matrix permeability and porosity in the reservoir as functions of time. It can be seen that, compared with the case without considering changes in porosity and permeability, as the system operating time increases, the permeability and porosity in the present model continuously increase. Although the growth rate is relatively slow at the beginning, it increases sharply after the system has operated for about 2 500 d. The main reason for the above phenomenon is that the low-temperature zone (the dark-blue region in the cloud map) further expands, and the thermal contraction effect in the low-temperature zone is significantly greater than that in the medium- and low-temperature zones. The larger the area of the low-temperature zone, the stronger the overall thermal contraction effect of the matrix, eventually producing qualitative change. The resulting manifestation in reservoir porosity and

Fig. 10

Figure 11: Fig. 10

Fig. 11

Figure 12: Fig. 11

permeability is a sharp increase in the growth rates of both. In summary, it can be inferred that thermal contraction of the reservoir matrix is the main factor leading to changes in porosity and permeability.

Figure 10 Variation of the average flow velocity of the main fracture over time

Fig. 10 The variation of the average flow velocity of the main fracture over time

Figure 11 Variation of the average flow velocity of the matrix over time

Fig. 11 The variation of the average flow velocity of the matrix over time

Figure 12 Variation of porosity and permeability over time

Fig. 12 The variation of porosity and permeability over time

2.5 Analysis of the influence of supercritical CO_2 on system heat exchange

To study the influence of the nonlinear variation of the physical parameters of supercritical CO_2 in the reservoir on its heat-exchange performance, the point on the fracture (as indicated by the yellow dot in Figure 2) was selected as the probe point, and the nonlinear changes over time of the thermophysical parameters of supercritical CO_2 were monitored. As shown in Figure 13, as the temperature of the EGS reservoir continuously decreases, the values of the various thermophysical parameters of supercritical CO_2 show an upward trend. The parameters are analyzed as follows.

1) Constant-pressure specific heat: Constant-pressure specific heat is one of the indicators that determine the heat-carrying capacity of a fluid per unit mass. The constant-pressure specific heat of supercritical CO_2 remains relatively low at the beginning, about 1 400 J/(kg·°C). The lower specific heat means that less heat is required to raise the temperature by one unit, thereby enabling a faster heat-absorption rate. Meanwhile, the flow velocity of supercritical CO_2 is relatively large, so the absorbed heat can be rapidly carried away; therefore, the system can maintain a relatively

Fig. 12

Figure 13: Fig. 12

Fig. 13

Figure 14: Fig. 13

high heat-extraction rate. As the temperature continuously decreases, its specific-heat curve exhibits relatively large fluctuations.

2) Density: Similar to constant-pressure specific heat, density is also one of the indicators for evaluating the heat-carrying capacity of a fluid per unit mass. The density of supercritical CO_2 fluctuates considerably with temperature at the same pressure. In the relatively high-temperature region it is about 200 kg/m^3, and as the reservoir temperature decreases it can increase to 800 kg/m^3, but the average density is less than 500 kg/m^3.

3) The thermal conductivity of supercritical CO_2 gradually increases as temperature decreases, with an average value of about 0.07 W/(m · °C).

4) Dynamic viscosity has an important influence on the convective heat transfer of CO_2. The lower the dynamic viscosity, the smaller the resistance that CO_2 must overcome when seeping through fractures and the matrix, and therefore the smaller the attenuation of flow velocity. The dynamic viscosity of supercritical CO_2 gradually increases with temperature, but the amplitude is not large; it remains within the same order of magnitude, with an average value of about 2.5×10^{-5} Pa · s.

From the above phenomena, it is not difficult to see that although the thermophysical parameters of supercritical CO_2 have a direct influence on convective heat transfer in the system, the degree of influence of each parameter is different. Correspondingly, the influence of EGS on each parameter is also different. For specific heat, at the beginning

the value remains at a low level (about 1 400 J/kg · °C; the units are omitted below). As the low-temperature region diffuses to the probe point, the value begins to rise rapidly from day 500, jumps from 1 400 to 2 600, then immediately decreases, and tends to be stable at about 2 500 d. Specific heat capacity is a function of both temperature and pressure. According to the preceding analysis, the reservoir pressure can reach equilibrium within a short time (120 d), so the main factor causing the change in specific heat capacity at this time is the change in temperature. When the pressure is unchanged, the specific heat capacity increases as the temperature decreases, which explains the reason for the sudden increase in specific heat capacity. After the specific heat capacity reaches its peak value, it decreases rapidly. A possible reason is that the temperature approaches the critical temperature, resulting in an abrupt change in its value; however, this still needs to be further analyzed and confirmed in future studies.

(a) Specific heat capacity and thermal conductivity

(b) Density and dynamic viscosity

Fig. 13 Variation of thermal-property parameters of supercritical CO_2 over time

In addition, the reason that the specific heat capacity value still tends to be stable is that, by this time, the original surplus heat in the reservoir region has already been carried away, and the heat-conduction rate of the reservoir and the convective heat-transfer rate of supercritical CO_2 have temporarily reached dynamic equilibrium. Therefore, the temperature can remain stable, causing the specific-heat-capacity curve to become stable. Similarly, although EGS has different degrees of influence on the various thermal-property parameters of supercritical CO_2, their mechanisms of action are similar; that is, when the pressure change is not large, they are mainly controlled by temperature. Density, like specific heat capacity, is a decisive factor affecting convective heat transfer by supercritical CO_2: the greater the density, the greater the heat exchange per unit volume. As the temperature decreases, the density gradually increases from 300 (unit: kg/m^3, omitted below) to a maximum of 850, nearly approaching that of liquid water (1 000). Therefore, it can be considered that supercritical CO_2 has a more obvious heat-exchange advantage in low-temperature geothermal systems. Dynamic viscosity is also an important factor affecting convective heat transfer by supercritical CO_2. The smaller its value, the less resistance supercritical CO_2 needs to overcome in fractures. Although dynamic viscosity changes to a certain extent, it generally remains in the same order of magnitude (10^{-5}), and is still very low compared with liquids such as water (about the order of 10^{-3}). Therefore, overall, it has little effect on dynamic viscosity, and, as ultimately reflected in heat-transfer performance, its influence can be regarded as small. The thermal conductivity likewise increases as the temperature decreases. Considering that, when CO_2 percolates in fractures and the matrix, it has sufficient contact area with the rock matrix, and that the EGS scale is relatively large, CO_2 has sufficient time to conduct heat while flowing from the injection well to the production well; therefore, the influence of thermal conductivity is relatively small.

3 Conclusions

This study proposed a THM-coupled CO_2-EGS model that considers the dynamic evolution of dry-hot-rock reservoir porosity, and implemented it using numerical simulation. Through analysis of the model results, a series of conclusions were obtained. These conclusions have certain reference value for future practical EGS projects, are conducive to promoting the commercialization process of dry-hot-rock geothermal resource development in China, and also help advance the achievement of carbon-emission-reduction targets.

1) The coefficient-form PDE interface built into the finite-element software COMSOL Multiphysics was secondarily developed to construct governing equations for the seepage field and temperature field in a dry-hot-rock reservoir matrix. The dynamic-evolution model of porosity was coupled into a dual-medium model containing discrete fractures and porous media. Finally, a new CO_2-EGS model was established and fully coupled solution

was performed. The model was verified using the analytical solution for fracture heat transfer. The results show that the two sets of calculation results are highly consistent.

2) As supercritical CO_2 diffuses rapidly along fractures and the reservoir matrix, the EGS reservoir temperature continuously decreases, producing a "high-temperature wave peak phenomenon" ; the reservoir stress is continuously redistributed and reaches equilibrium after about 120 d of system operation; changes in matrix pore pressure and thermal contraction lead to displacement of the reservoir matrix, and permeability and porosity continuously increase, among which the influence of thermal contraction of the matrix accounts for the major part.

3) The thermal-property parameters of supercritical CO_2 have a direct influence on convective heat transfer in the system, but the degree of influence of each parameter is different. Correspondingly, the influence of EGS on each parameter is also different. With changes in reservoir pressure and temperature in the EGS, the thermal-property parameters of supercritical CO_2 change considerably, but temperature is the main influencing factor. Specific heat capacity, density, thermal conductivity, and dynamic viscosity all show nonlinear increasing trends with increasing system operation time. In addition, EGS has an influence on supercritical

CO_2 flow velocities in the matrix and main fractures are highly correlated, thereby directly affecting the convective heat-transfer performance of the system.

This study only calculated and analyzed the results under one operating condition. Because the properties of supercritical CO_2 differ greatly under different temperature and pressure conditions, the convective heat-transfer performance of supercritical CO_2 under other operating conditions still requires further study.

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Note: Figure translations are in progress. See original paper for figures.